

## Three Degree-of-Freedom Architecture for Hand-Controllers and Robots

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The goal of this work was to develop a new mechanical architecture—for actively powered haptic (“force-feel”) hand-controllers and robotic manipulators—that offers enhanced performance in terms of combined work-space size, position and force control accuracy, and payload. For hand-controllers, these attributes have obvious impact on the subjectively perceived “feel” of interactions with virtual or telemanipulated environments.

The moving structural components of a hand-controller or manipulator form the mechanical linkage that couples force and motion between the device’s actuators (motors) and end-effector. Thus, the linkage’s architecture directly determines not only the work space but also transmission characteristics such as dynamic range (comparing maximum usable force to friction) and bandwidth (frequency content of deliverable force and motion) that define control accuracy and contribute to payload capacity.

A novel three-degree-of-freedom (DOF) linkage architecture was devised, offering significant improvement over prior technology with respect to the above listed performance criteria. The innovative architecture (figure 1) is a mechanism composed of 10 rigid links that connect 12 single-DOF rotary joints. The links and joints are arranged in three loops that couple a handgrip or robot end-effector (D) to three rotary actuators (A, B, and C). The moving links do not carry actuator weight and inertia since A, B, and C are all mounted on a common base (unlabeled link 1). This frees more of the actuator force budget for useful work, that is, payload. Because the base link does not move, more powerful and typically heavier actuators can be used without the need for more massive moving support structures. This lower inertia improves acceleration response and expands structural bandwidth for better control at high frequencies.

The architecture requires no belt, cable, pulley, or screw transmission elements, all of which can be backlash-, friction-, or compliance-prone and that would therefore compromise end-effector force and position control. The actuators can be embodied by COTS (commercial, off-the-shelf) rotary electric

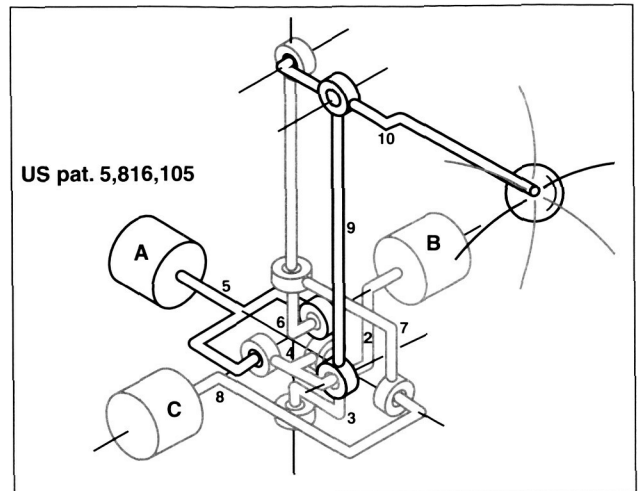


Fig. 1. Three-DOF parallel mechanism.

motors and the other joints by COTS backlash-free, low-friction ball bearings. Enhancing usable human and actuator force levels while minimizing losses to friction increases dynamic force range and is critical for back-drivability and the feel of hand-controllers.

The multiple-loop configuration of the linkage forms a so-called “parallel” mechanism, universally acknowledged as being structurally stiffer than competing “serial” designs. Greater stiffness is key to enhanced structural and control bandwidth, as well as improved position control accuracy.

The linkage work-space volume is correspondingly larger than that of prior three-DOF parallel configurations, approaching the work space of serial devices. This new architecture’s work space is bounded by the singularity at the sphere of maximum reach typical of all arm-like devices and by singularities in the sphere’s equator—the plane defined by the three actuator axes. In general, work-space singularities correspond to locations at which the linkage loses its ability either to move or to apply force in one or more directions.

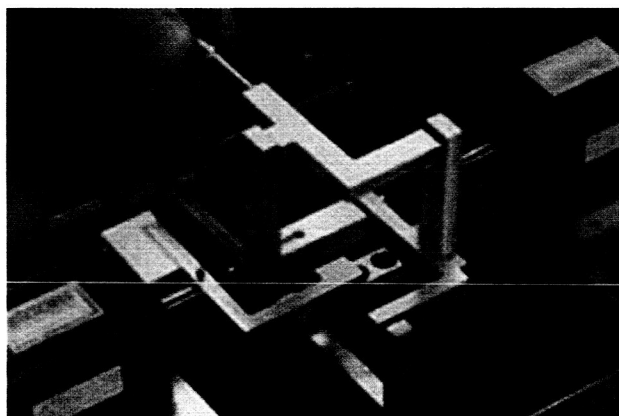
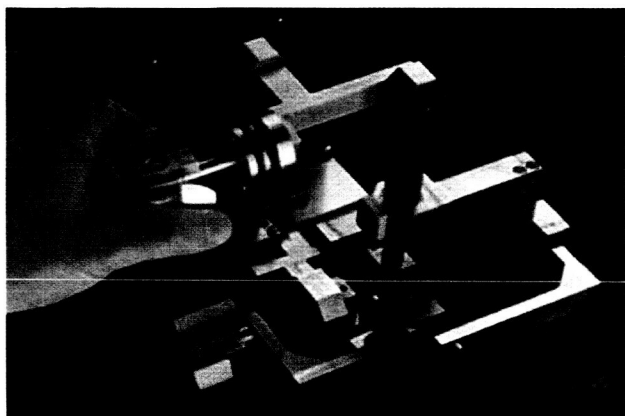
The linkage is composed of the minimum number of links and rotary joints in which all three actuators can be supported on a common base, giving the architecture fewer component parts than other three-DOF, spatial, all-rotary joint mechanisms. Fabrication and assembly constraints for the linkage are relatively simple: only the intersection of joint axes within two of the mechanism loops and the parallelism of joint axes in the third loop are mandatory. A closed-form potential energy analysis

demonstrates that, in theory, the linkage can be statically balanced for all base link orientations and also provides a three-step link mass-distribution procedure to achieve the balance. Perfect static balance obviates the need for actuator or external forces to support unbalanced linkage weight for any pose, freeing up more force for useful work.

Finally, the three-DOF architecture is scalable from large crane-sized construction and material-

handling equipment down to micro-machines for use in applications such as minimally invasive surgery. Arm- and finger-scale three-DOF force-feel joysticks (figure 2) demonstrate a portion of this scalability.

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*Fig. 2. Arm- and finger-scale force-feel hand-controllers.*

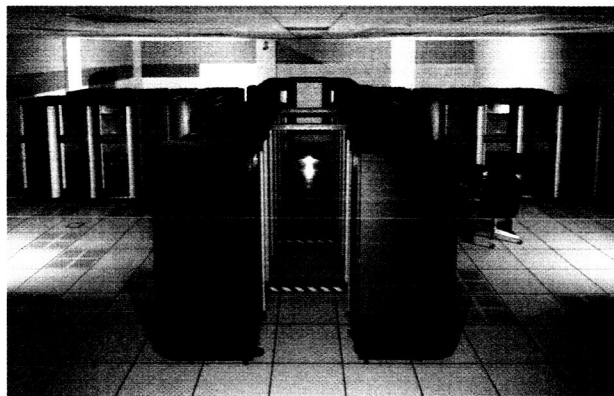
## **Performance of the COSMOS Multi-Level Parallelism Molecular Dynamics Code on the 512 CPU Origin System**

**James R. Taft**

Ames recently purchased an SGI 512 CPU Origin 2000 system. The system has been named Lomax, after the late celebrated Ames researcher Harvard Lomax. The Lomax system is the largest single shared-memory multi-processor system in the world (see figure 1). It is the result of an Ames-driven partnership with SGI to push the limits of single-system shared memory designs. It is believed that large CPU count single-system designs offer many potential advantages in those research areas that require very high levels of parallel computational performance. This system has demonstrated over 60 billion floating-point operations per second (60 GFLOP/sec) of sustained performance for the

production computational fluid dynamics (CFD) code OVERFLOW-MLP (13 times that of a 16 CPU C90 system). This system offers even higher performance potential for molecular dynamics simulations.

Recently, the Lomax system was used as the parallelization testbed for the COSMOS ab initio



*Fig. 1. The Ames 512 CPU SGI Origin 2000 system.*